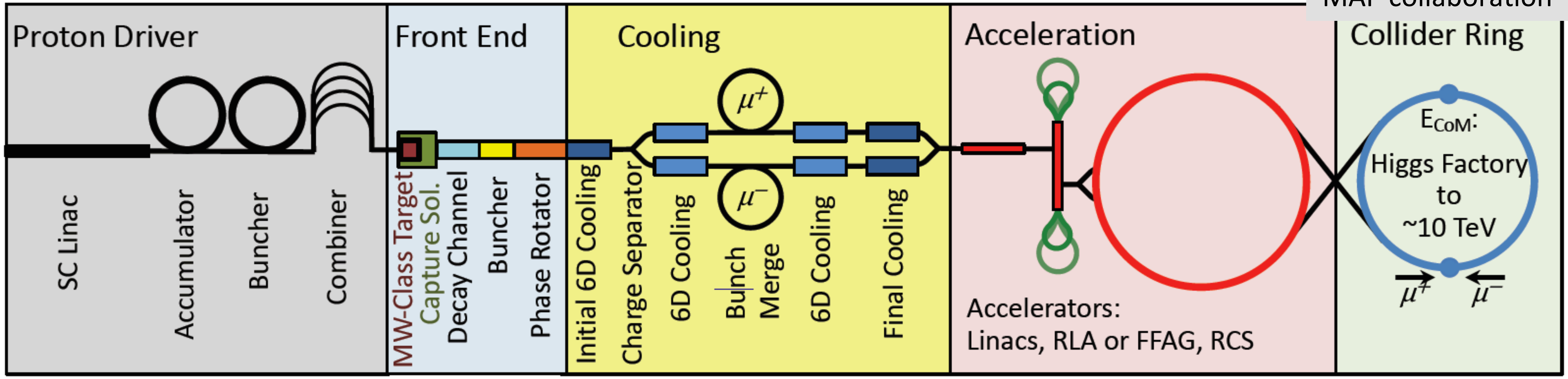
Muon Collider

Daniel Schulte for the forming international muon collider collaboration

Proton-driven Muon Collider Concept

MAP collaboration



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

Collision

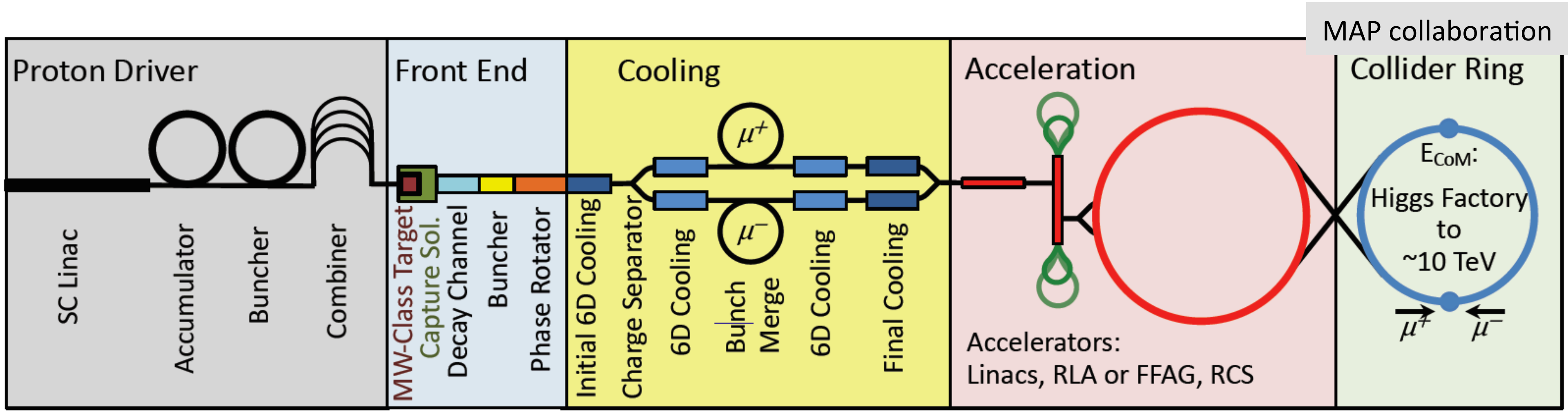
Pions decay into muons that can be captured

Work has been mainly performed in US (MAP Collaboration), test of muon cooling in UK
Some effort mainly in INFN on alternative

M. Biagini et al. H.08.00005

No CDR exists, no coherent baseline of machine, no cost estimate
US activity very much reduced after last P5
But many parts and no showstoppers

Renewed Interest



For European Strategy Update (ESU), the Laboratory Directors Group (LDG) appointed a working group (chair N. Pastrone) to review the muon collider
⇒ positive recommendation

LDG initiated an **International Muon Collider Collaboration**
CERN will host the study, we are finalising a Memorandum of Cooperation
current **CERN budget 2 MCHF/year** for the next 5 years

Council charged LDG to develop European Accelerator R&D Roadmap in 2021
- muon collider is included in this

Also note growing interest in other regions

International Muon Collider Collaboration

Objective:

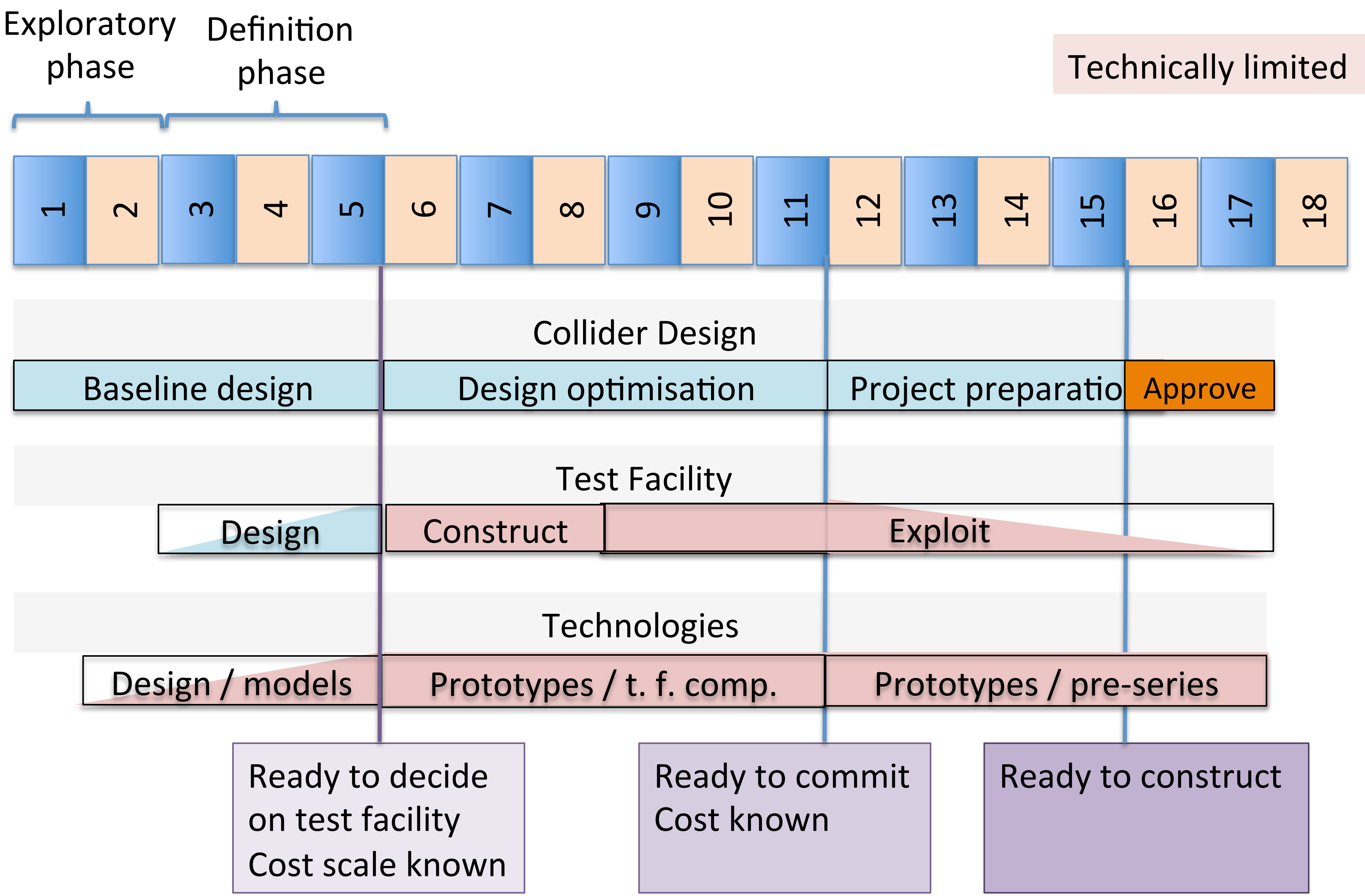
In time for the next European Strategy for Particle Physics Update, the study aims to **establish whether the investment into a full CDR and a demonstrator is scientifically justified**.

It will provide a baseline concept, well-supported performance expectations and assess the associated key risks as well as cost and power consumption drivers. It will also identify an R&D path to demonstrate the feasibility of the collider.

Scope:

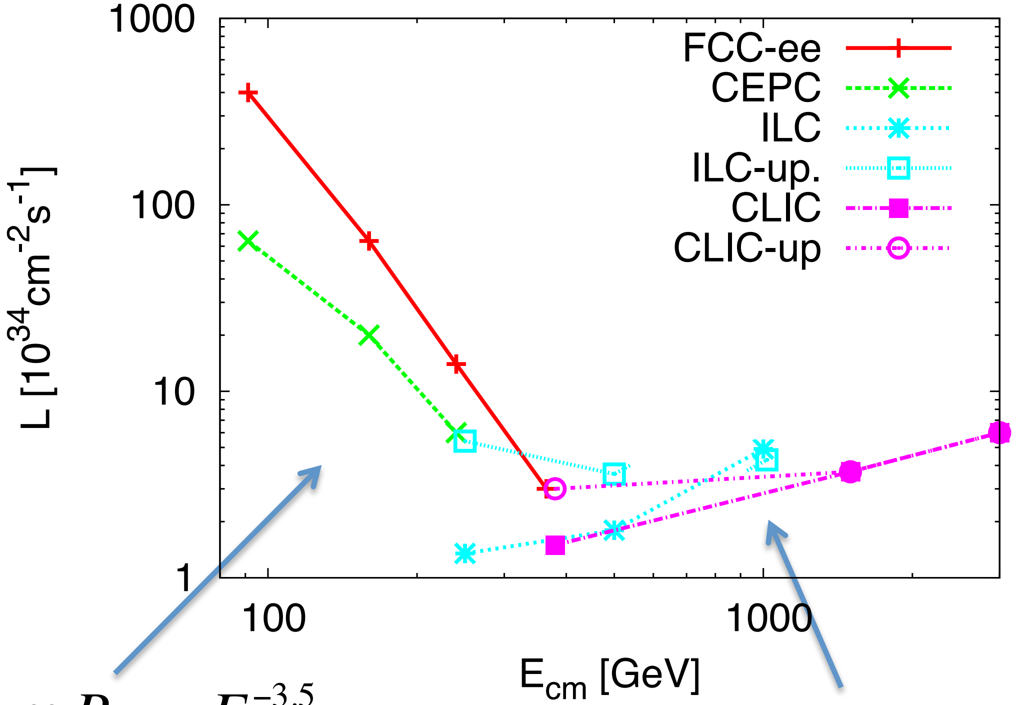
- Focus on two energy ranges:
  - **3 TeV**, if possible with technology ready for construction in 10-20 years
  - **10+ TeV**, with more advanced technology, **the reason to chose muon colliders**
- Explore synergy with other options (neutrino/higgs factory)
- Define **R&D path**

Potential Long-Term Timeline



Proposed Lepton Colliders (ESU)

Luminosity per facility



$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF}$

$$\boxed{L \gtrsim \frac{5\,\mathrm{years}}{\mathrm{time}} \left(\frac{\sqrt{s_\mu}}{10\,\mathrm{TeV}}\right)^2 2 \cdot 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

Maximum proposed energy CLIC 3 TeV

- Cost estimate total of 18 GCHF
  - In three stages
  - Largely main linac, i.e. energy
- Power 590 MW
  - Part in luminosity, a part in energy
- Similar to FCC-hh (24 GCHF, 580 MW)

Technically possible to go higher in energy

But is it affordable?
Cost roughly proportional to energy
Power roughly proportional to luminosity.

Luminosity goal increases with centre-of-mass energy squared

Comparing Luminosity in MAP vs. CLIC

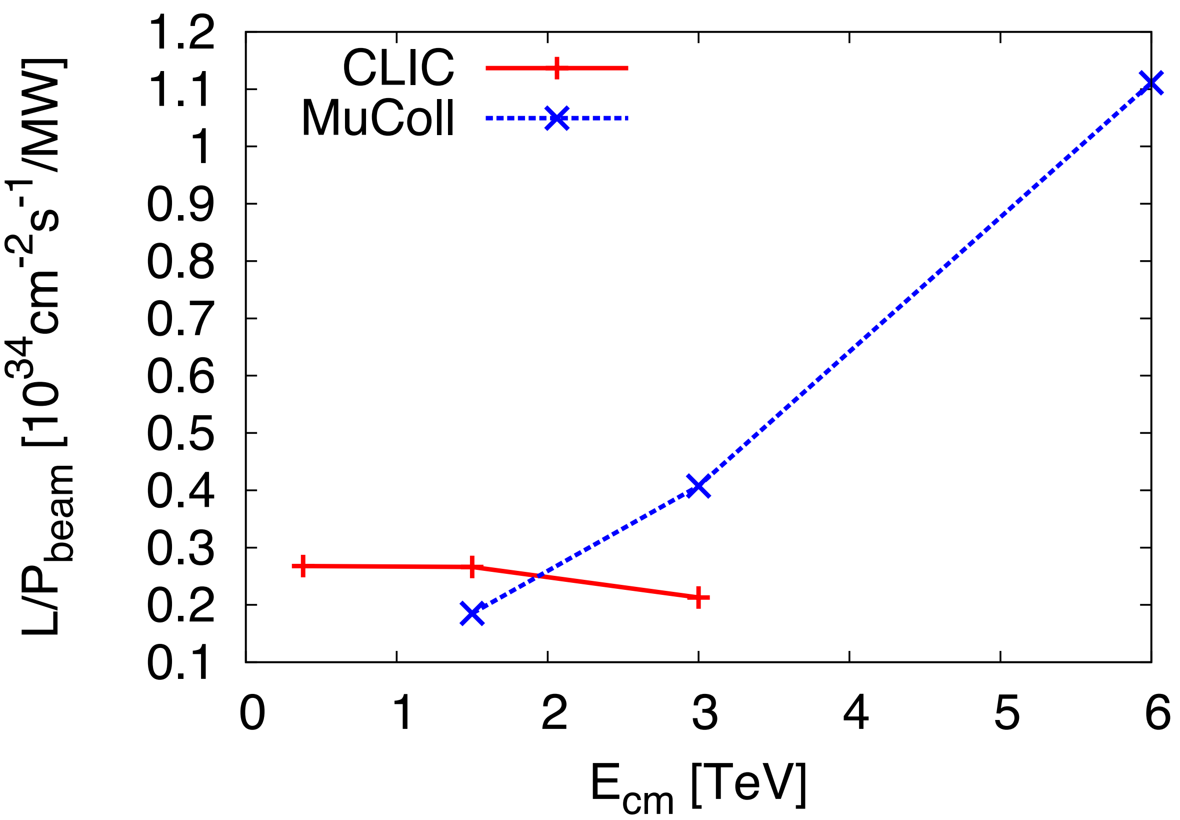
Linear colliders: Luminosity per beam power is independent of collision energy for same technology

CLIC is at the limit of what one can do (decades of R&D)

No obvious way to improve

$$\mathcal{L} \propto \frac{N}{\sqrt{\beta_x \epsilon_x}} \frac{1}{\sqrt{\beta_y \epsilon_y}} P_{beam}$$

Note: normalised emittances used, they do not decrease with energy



Muon collider: Luminosity per beam power can increase with energy

Potential for high energies

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

Luminosity Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Note: currently no staging
Would only do 10 or 14 teV

Reasonably conservative

- each point in 5 years with tentative target parameters
- FCC-hh to operate for 25 years
- Aim to have two detectors
- Might integrate some margins

Note: focus on 3 and 10 TeV
Have to define staging strategy

Tentative target parameters
Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} cm^{-2}s^{-1}	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Key Topics

10+ TeV is uncharted territory

- **Physics potential** evaluation
- Impact on the environment
  - The **neutrino radiation** and its impact on the site
- The impact of **machine induced background** on the detector, as it might limit the physics reach.
- **High-energy systems** after the cooling (acceleration, collision, …)
  - This can limit the energy reach via cost, power and beam quality
- **High-quality beam production** of cooled muon beam
  - MAP did study this in detail
  - Need to optimise and prepare test facility

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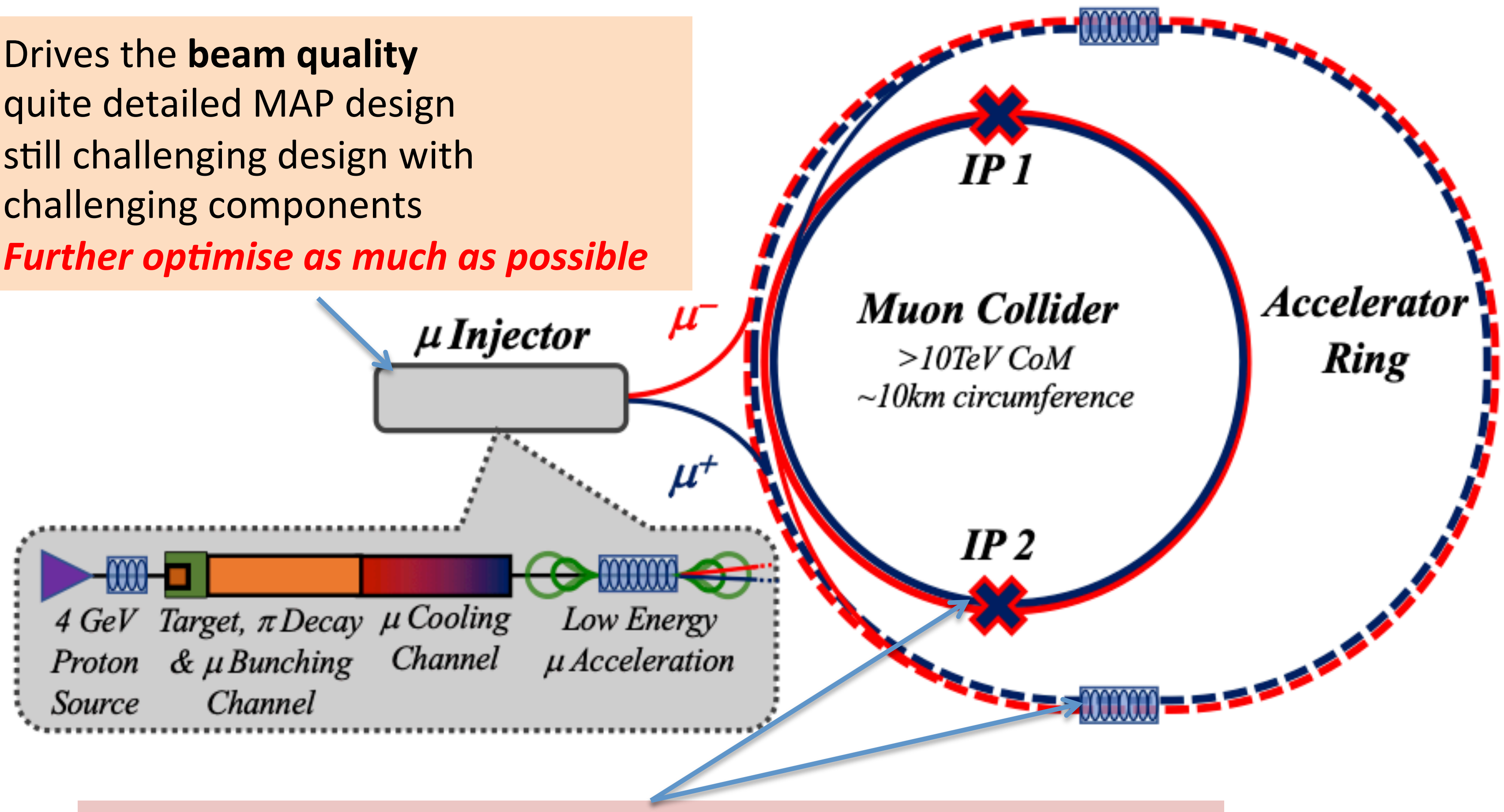
N. Craig, B.08.00001
Z. Liu et al. B.08.00004
X Wang et al., D.14.00005
R. Ruiz et al. H.08.00002
K.-P. Xi et al. H.08.00006
R. Capdevilla et al., H.08.00007

Not covered here

S. Pagan Griso et al., H.08.00001
C. Curatolo et al., B08.00002
N. Bartosik et al., B08.00003
L. Sestini et al., B08.00005
L. Buonincontri et al., B08.00006
M. Casarsa et al., D.14.00007
H. Weber et al., H.08.00003

Overall Considerations

Drives the **beam quality**
quite detailed MAP design
still challenging design with
challenging components
Further optimise as much as possible



Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring
Also impacts **beam quality**
Drives **neutrino radiation** and **beam induced background**
Improve compared to MAP design and design for high-energy

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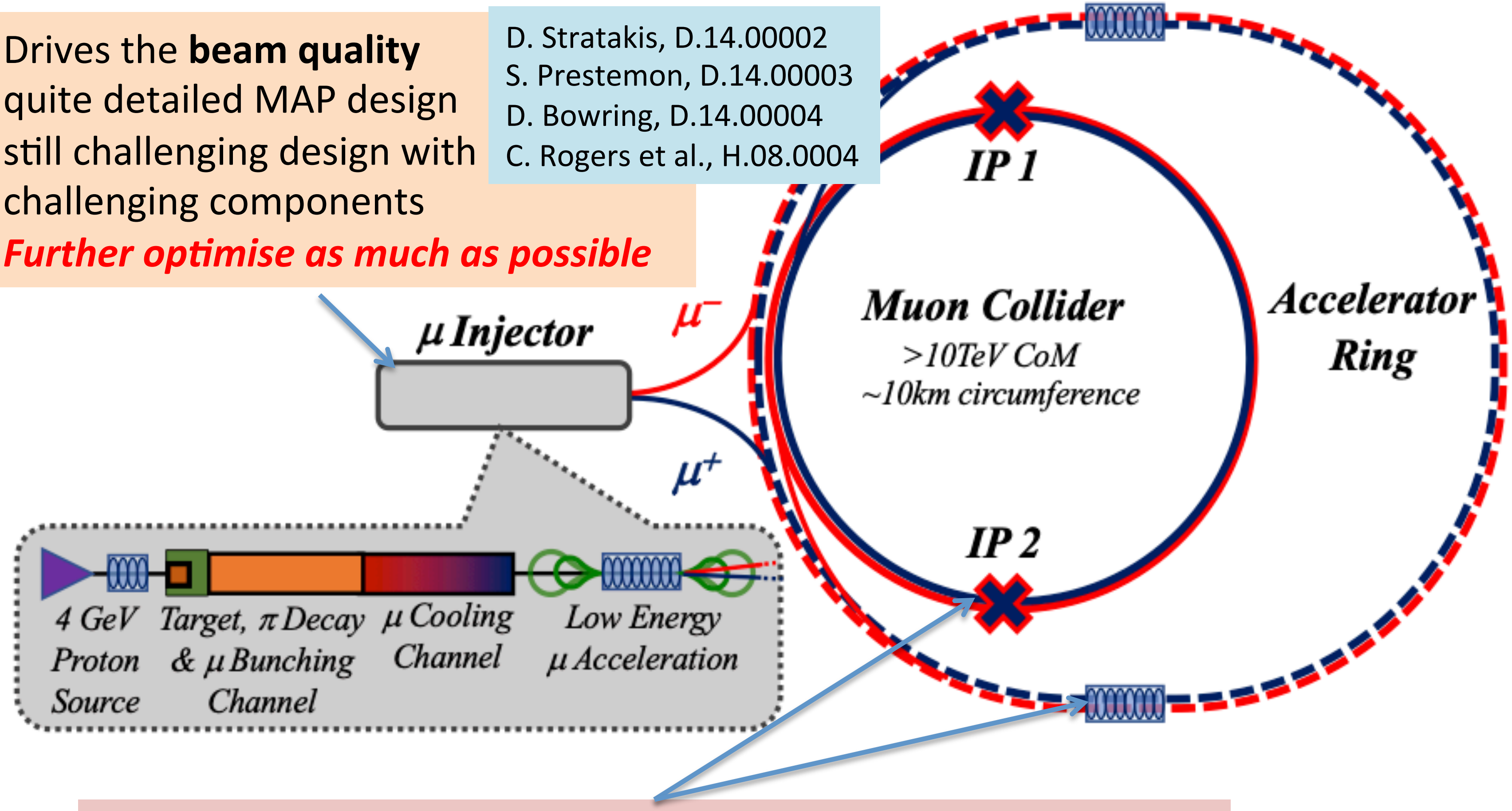
D. Stratakis, D.14.00002
S. Prestemon, D.14.00003
D. Bowring, D.14.00004
C. Rogers et al., H.08.0004



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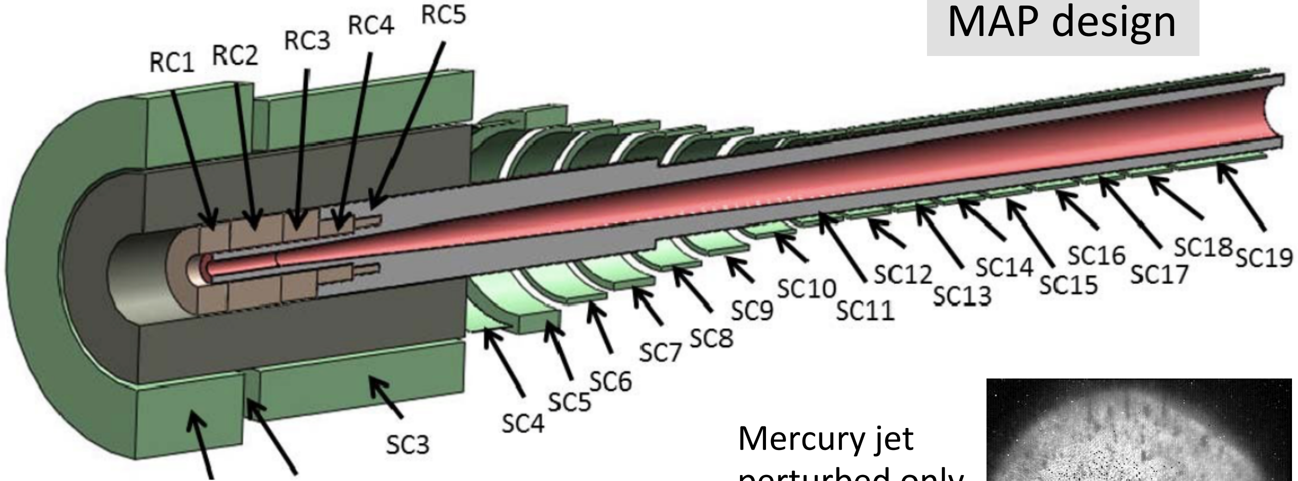
S. Prestemon, D.14.00003
E. Gianfelice-Wendt, D.14.00007

Source

Intense proton beam is challenging O(2x10^{14}) 8-GeV protons per pulse

MAP design

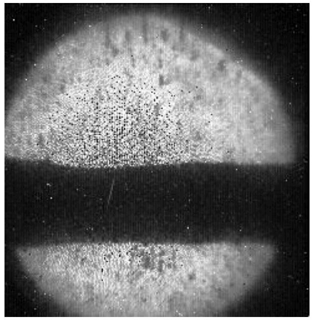


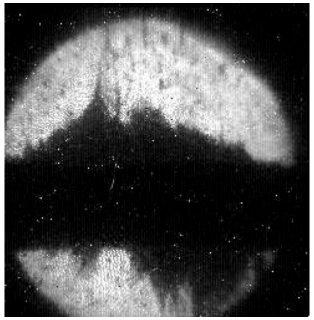
Target
- 1.3 MW proton beam
- **stress resistance**

High-field solenoid
- **radiation load/cooling**
- liquid mercury target successfully tested at CERN (MERIT)
- but solid target better for safety
- or beads
- or …

Radiation in downstream systems

Mercury jet perturbed only after beam has passed, recovers quickly enough

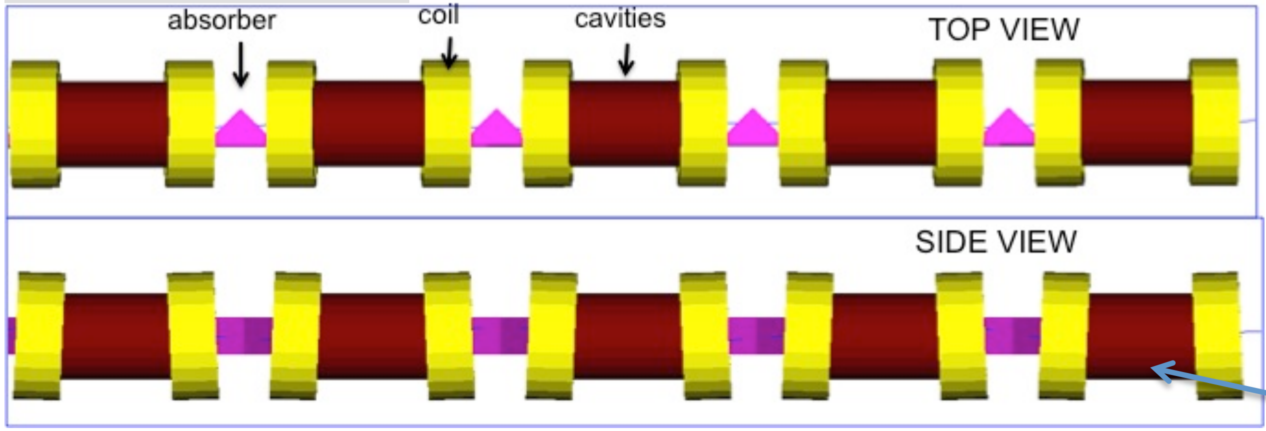




Starting to review what needs to be done
Feels ambitious but do not see showstopper

Muon Cooling Concept

MAP collaboration



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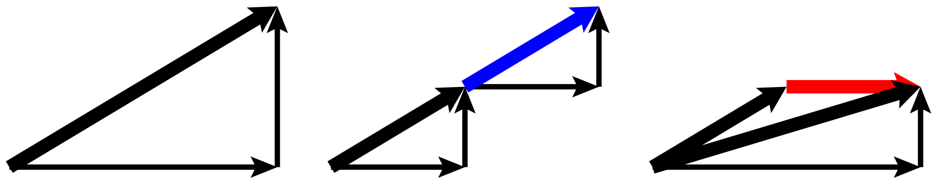
Superconducting solenoids
High-field normal conducting RF
Liquid hydrogen targets
Compact design

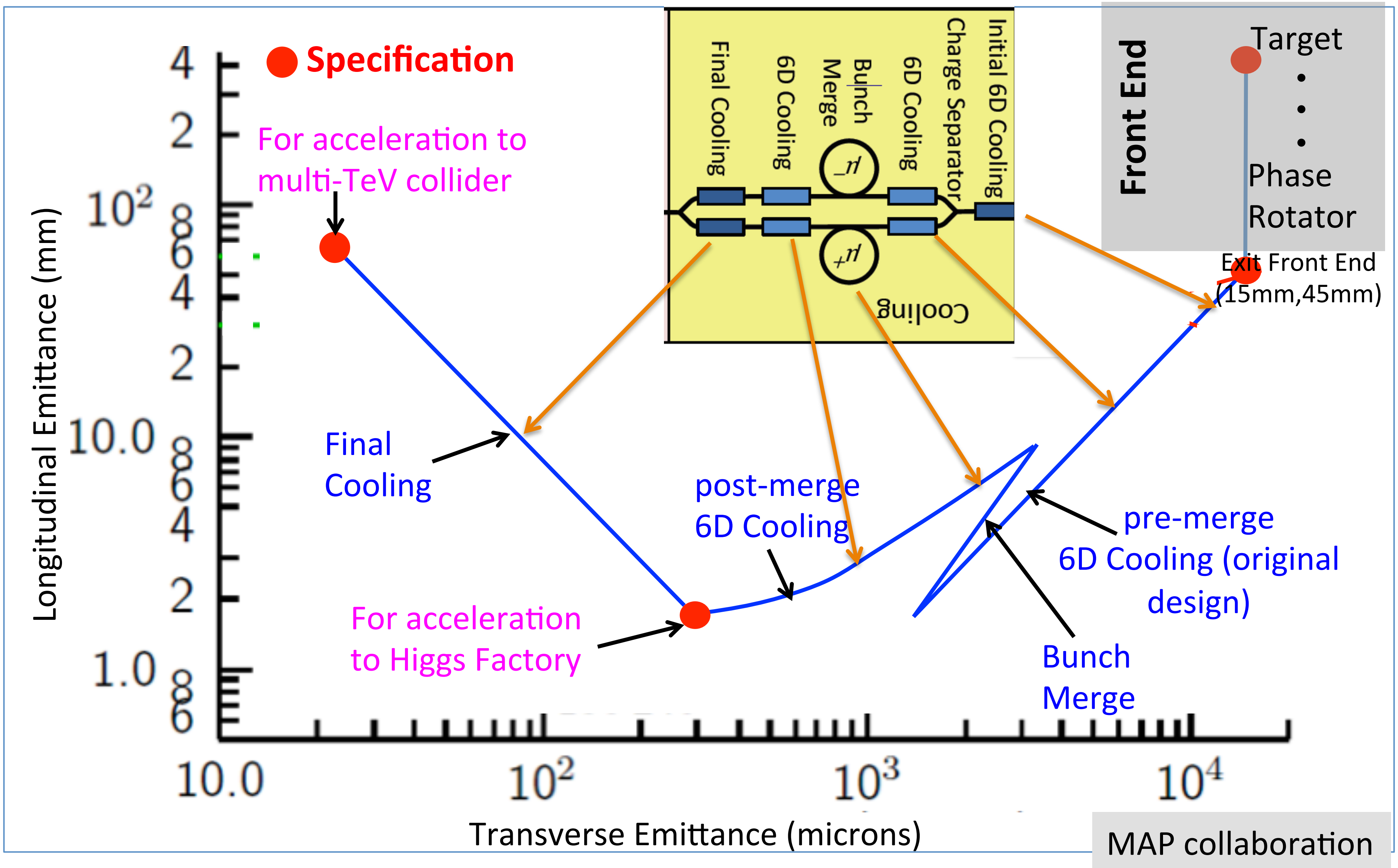


Limit muon decay, cavities with **very high gradient in a magnetic field**

Minimise betafunction with **strongest solenoids**

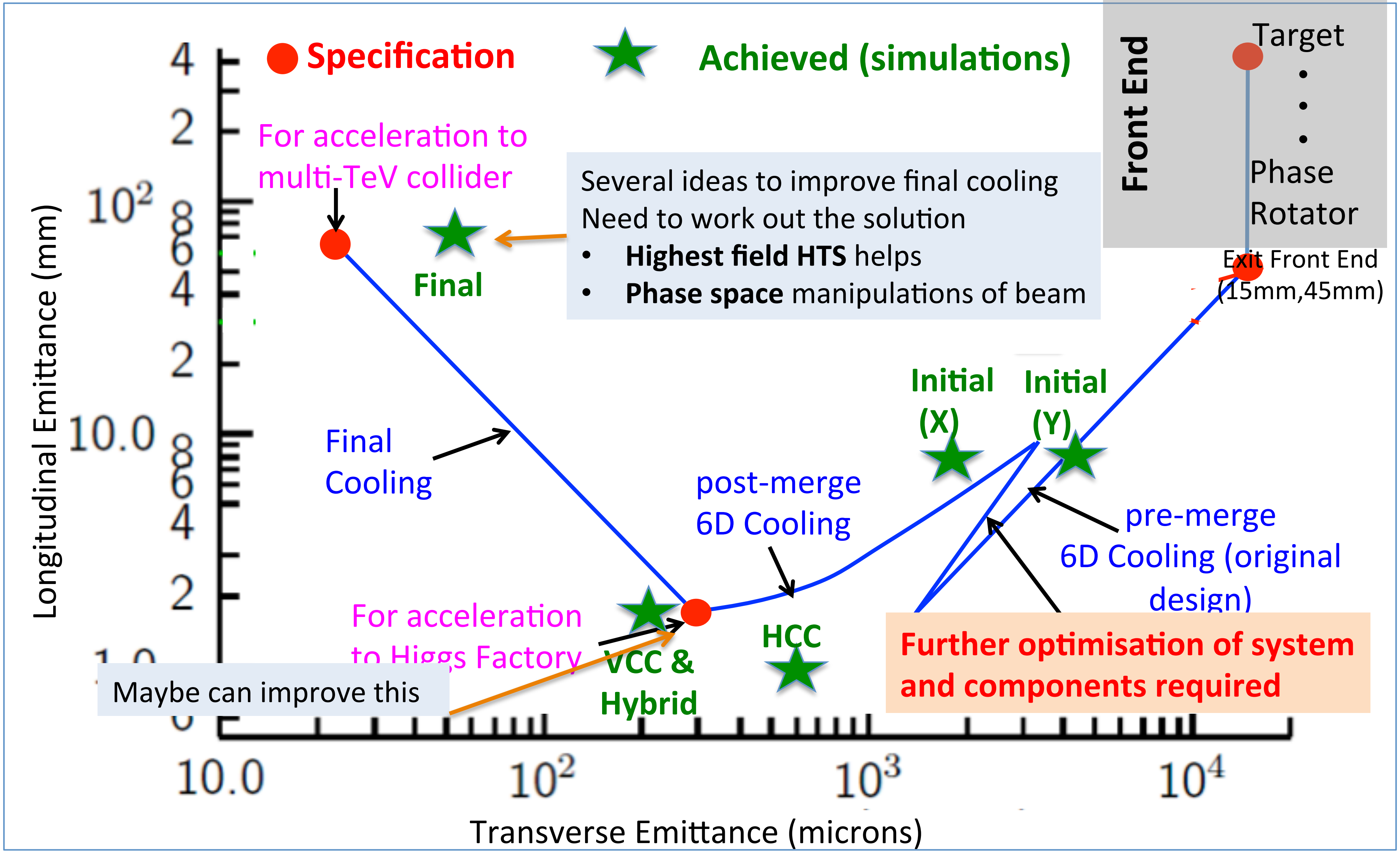
$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Cooling: The Emittance Path



Design Status

⇒ D. Stratakis, D.14.00002



Component Status

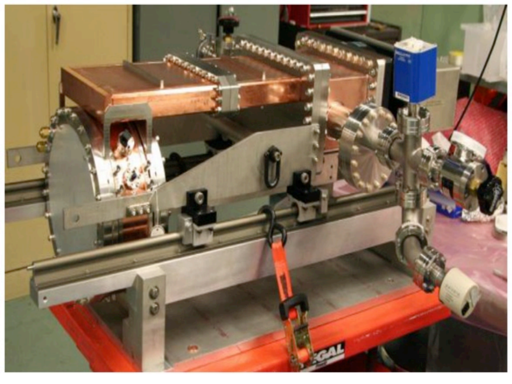
Cavities with very **high accelerating gradient in strong magnetic** field

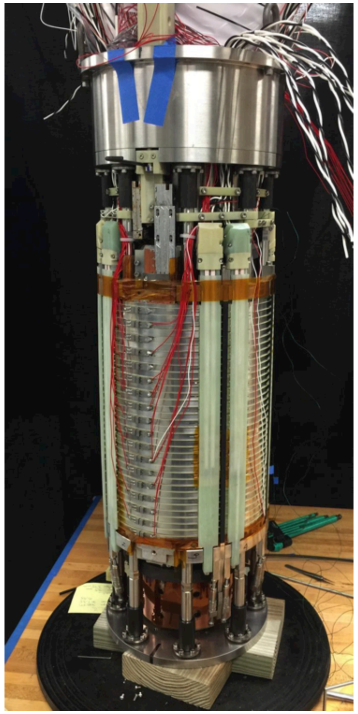
Very strong solenoids (> 30 T) for the final cooling
- simplified: Luminosity is proportional to the field

Promising performance, try to push further

MuCool: >50 MV/m in 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps

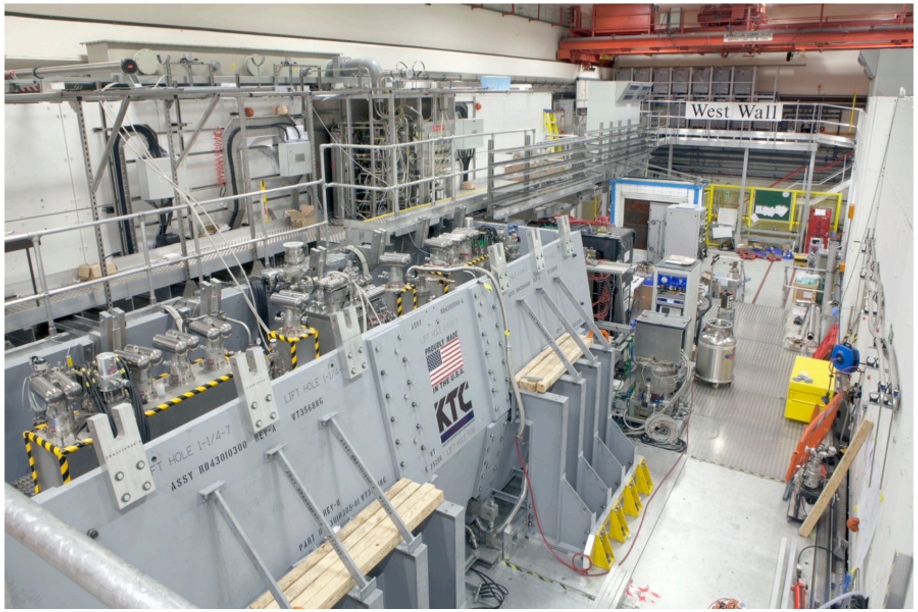




NHFML
32 T solenoid with low-temperature HTS

We would like to push even further

MICE (UK)



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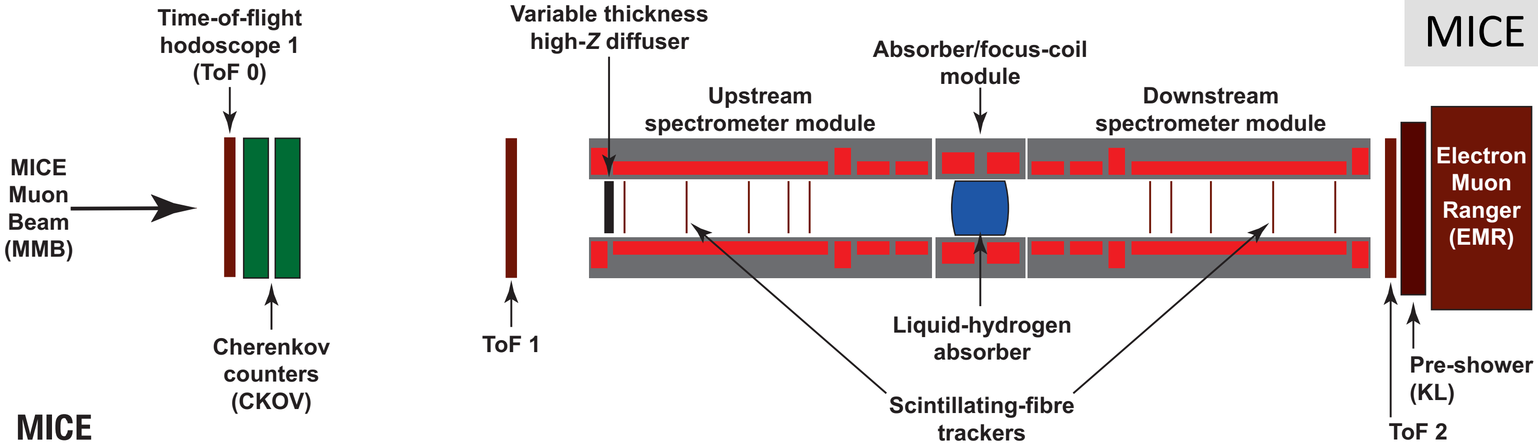
⇒ S. Prestemon, D.14.00003
⇒ D. Bowring, D.14.00004

Demonstration Status

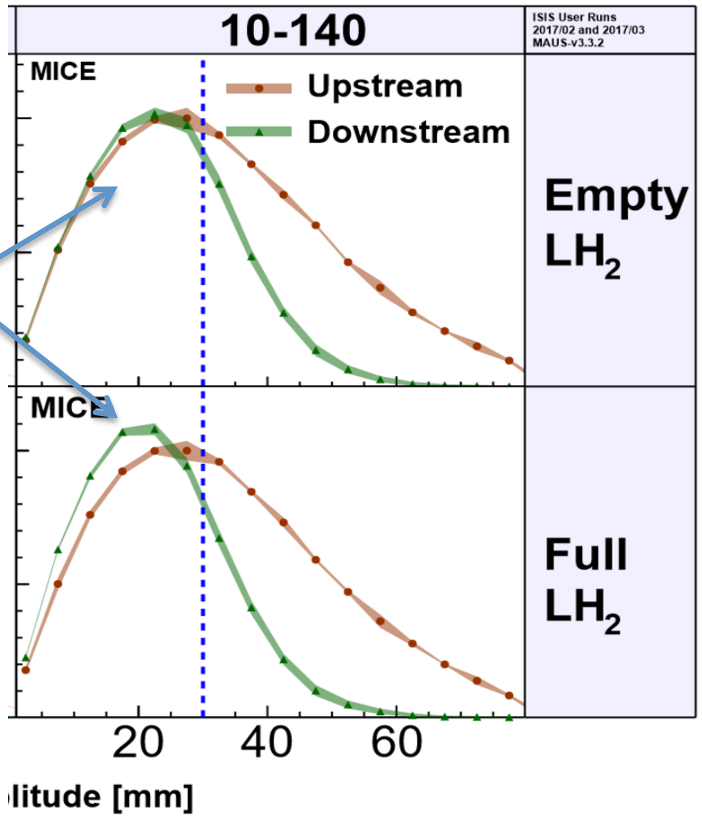
MICE collaboration



- ⇒ D. Stratakis, D.14.00002
- ⇒ C. Rogers et al., H.08.0004

More particles at smaller amplitude after absorber is put in place

Principle of ionisation cooling has been demonstrated

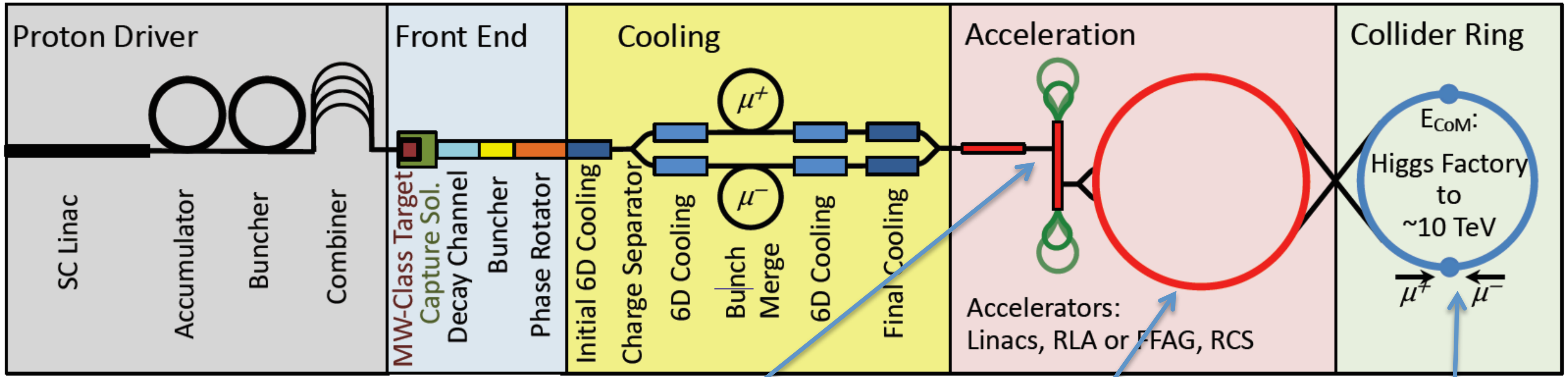


Nature volume 578, pages 53-59 (2020)

New test facility with better statistics

- **Integration of magnets, RF, absorbers, vacuum is engineering challenge**
- **For implementation after ESU**

High-energy Complex



⇒ S. Prestemon, D.14.00003
⇒ E. Gianfelice-Wendt, D.14.00007

Initial acceleration

Linacs/recirculating linacs

Detailed designs from MAP

Alex Bogacz

Final acceleration

- FFAG (static superconducting magnets)
- or RCS (rapid cycling synchrotron)

High-energy designs required

Start-to-end simulations

To be started

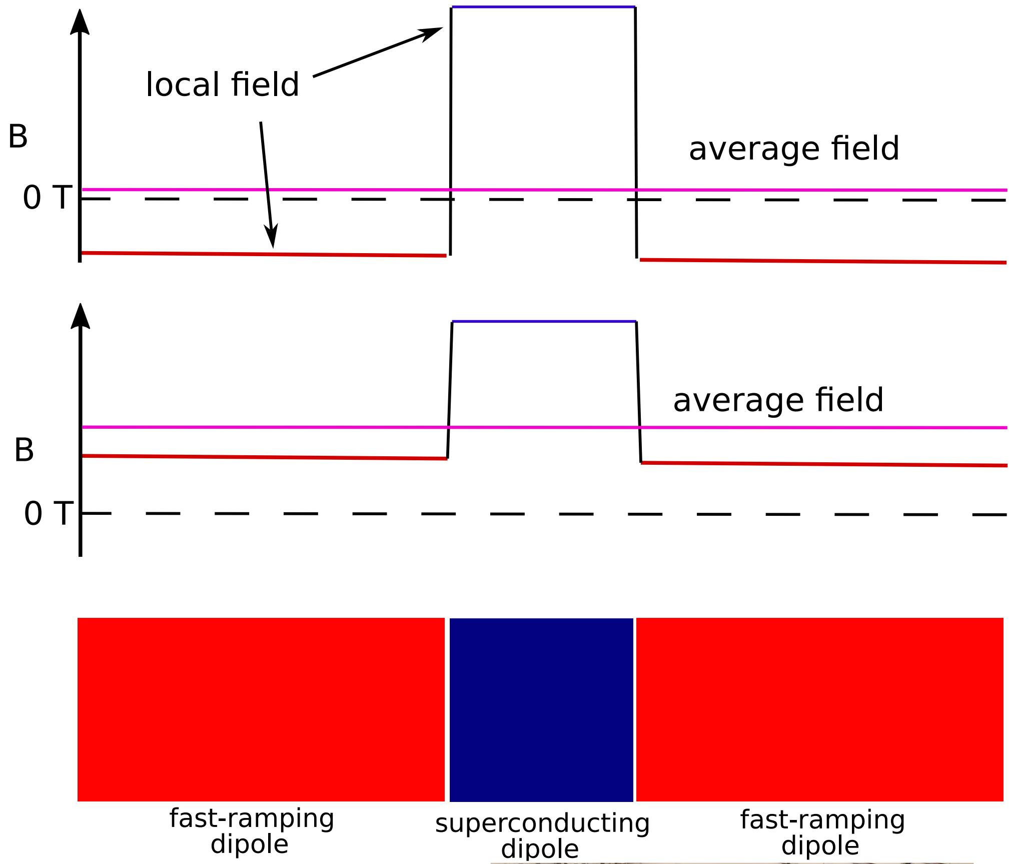
Collider ring

High-energy designs required

High-energy Acceleration

Rapid cycling synchrotron (RCS)

- Ramp magnets to follow beam energy
- Combine static and ramping magnets
- Possible circumference
    - 14-26.7 km at 3 TeV
    - O(30 km) for 10 and 14 TeV
- Power consumption of fast-ramping systems is important

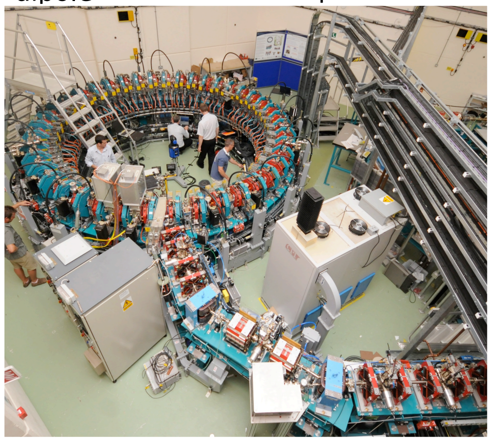


FFAG

- Fixed (high-field) magnets but large energy acceptance
- Challenging lattice design for large bandwidth and limited cost
- Complex high-field magnets
- Challenging beam dynamics

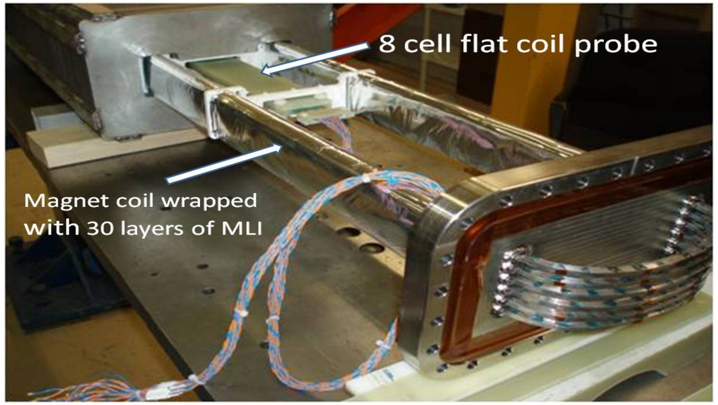
EMMA proof of FFA principle

Nature Physics 8, 243–247 (2012)



Key RCS Components

Fast-ramping, normal-conducting magnets
(5 km of 2 T of per TeV beam energy in hybrid design)
Design optimisation needed



⇒ S. Prestemon, D.14.00003

Test of **fast-ramping normal-conducting magnet** design

Fast, high-field HTS ramping magnets could benefit 10+ TeV design
Need O(100) improvement in speed and O(few) in amplitude

Acceleration 0.3 to 1.5 TeV				
Length	km	13.8	26.7	26.7
8 T dipole	km	2.36	2.36	-
L_{ramp}	km	6.3	15.8	18.2
B_{ramp}	T	-2 / 2	-1 / 1	0.34 / 1.7

FNAL
12 T/s HTS
0.6 T max

Need to push in field and speed

Power converters (recovery of energy in ramping magnets, O(200 MJ) at 14 TeV) *Design started*

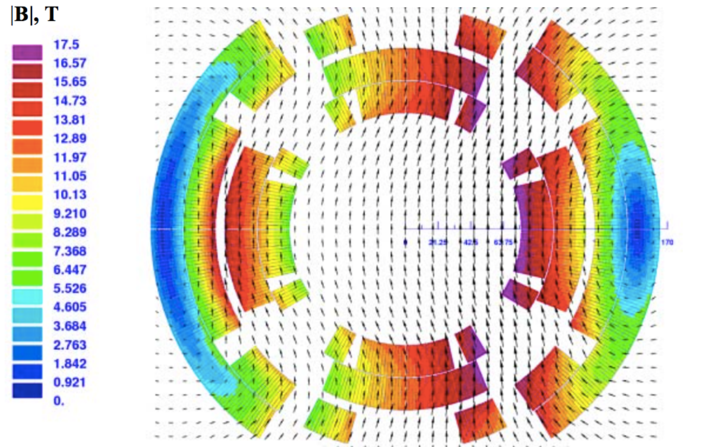
RF (also for FFA):
Single-bunch beam, high charge (10 x HL-LHC), maintain small longitudinal emittance, high efficiency
Design started

Collider Ring

High field dipoles to minimise collider ring size and maximise luminosity
4.5 km at 3 TeV, 10/14 at 10/14 TeV

⇒ S. Prestemon, D.14.00003
⇒ E. Gianfelice-Wendt, D.14.00007

Combined function magnet design



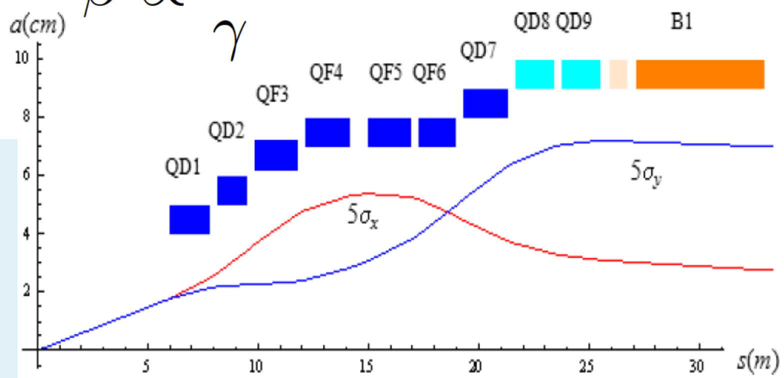
V.V. Kashikhin et al.

Beam loss protection O(500 W/m)

- MAP shielding solution for 3 TeV: 150 mm aperture and 30-50 mm shielding

Strong focusing at IP to maximise luminosity
Becomes harder with increasing energy
Lattice and magnet design challenge

$$\beta \propto \frac{1}{\gamma}$$



Lattice design/beam dynamics
e.g. Short bunch preservation (1 mm) in large ring

- Careful control of longitudinal motion
- Beam dynamics of frozen beam
- Synergy with light sources might exist

Technology Progress

⇒ S. Prestemon, D.14.00003

Important progress on high-field magnets for many projects, HL-LHC, FCC, …

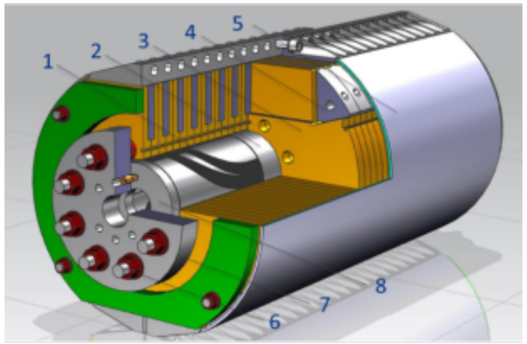
General development of magnets (Nb_3Sn and HTS) in all regions

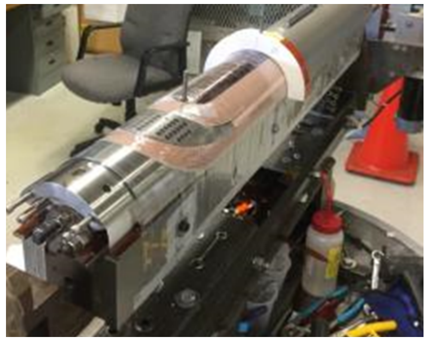
Consider more conventional for first stage, more advanced technology for second stage

U.S. MAGNET DEVELOPMENT PROGRAM

Fermilab
50 Years of Discovery

15 T dipole demonstrator
60-mm aperture
4-layer graded coil





Development of conductors (FCC)

Participants

Switzerland: CERN

Japan: KEK, FURUKAWA ELECTRIC, JASTEC

Russia: BOCHVAR INSTITUTE OF INORGANIC MATERIALS JSC VNIINM, TVEL

Korea: KISWIRE

China: Western Superconducting Technologies Co., Ltd.

Austria: TU WIEN

Germany: TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG

Italy: Columbus Superconductors

Finland/USA: LUVATA SPECIAL PRODUCTS

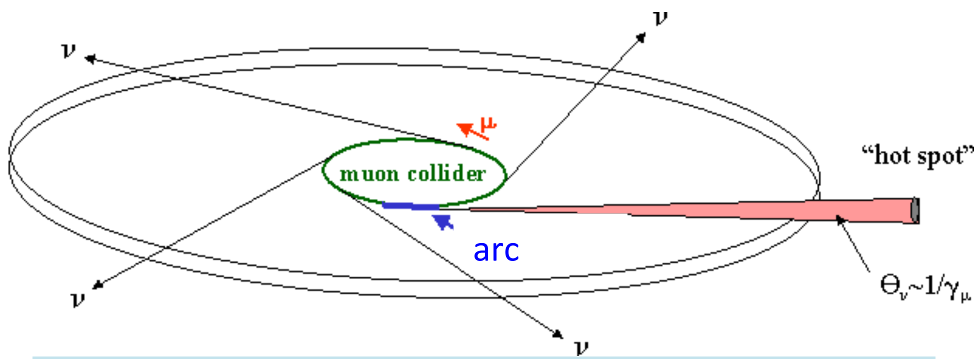
Italy: SPIN

Switzerland: UNIVERSITÉ DE GENÈVE

7 companies, two universities and two national research institutes

Magnet progress is important
Need to share magnet work for muon collider

Neutrino Radiation



Important luminosity limitation
Particularly high in direction of the straights
⇒ buy land in direction of straights

Have to still cover arcs

Typical legal limit 1 mSv/year

MAP goal < 0.1 mSv/year

No legal procedure < 10 μSv/year

LHC achieved < 5 μSv/year

No mitigation, 500 m deep tunnel:

3 TeV: close to LHC

14 TeV: around legal limit

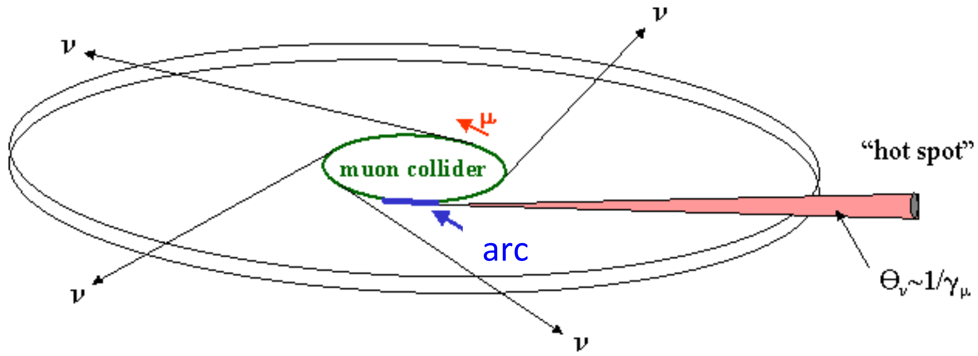
Needed to find a solution

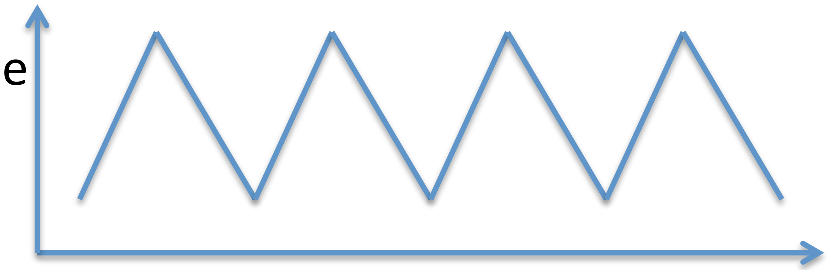
Work with **Radiation Protection, Civil Engineering, Geometers** and **Lattice Design** started to find solutions

Mitigate radiation to a level as low as reasonably achievable

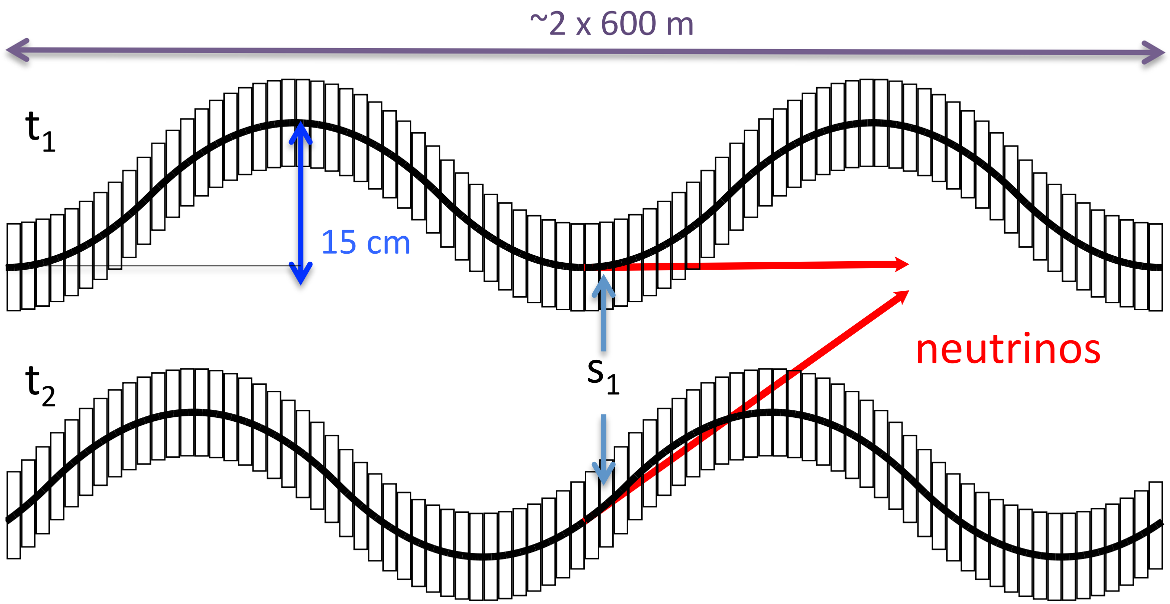
Similar to LHC

Neutrino Radiation Mitigation Proposal





Mokhov, Ginneken: move beam in collider aperture
Investigating: move collider ring components, e.g. vertical bending with 1% of main field



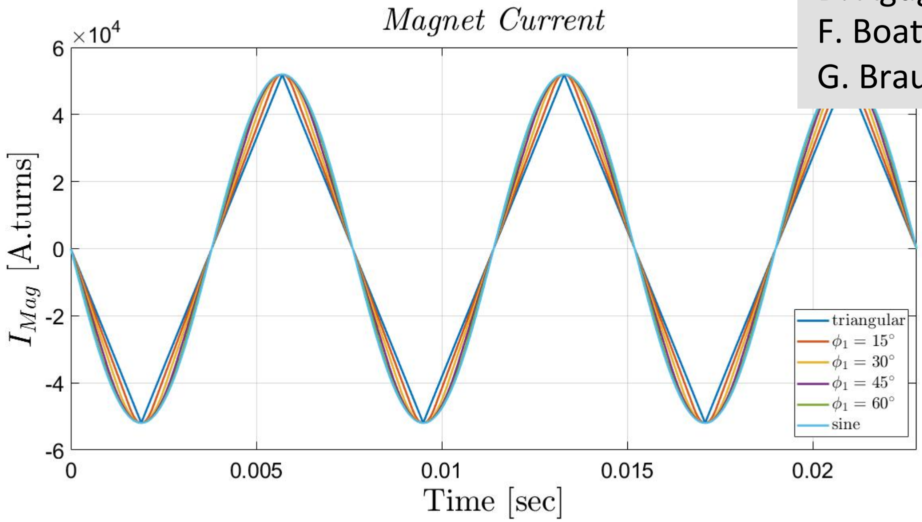
Opening angle ± 1 mradian

Even at 14 TeV
200 m deep tunnel would be comparable to LHC case

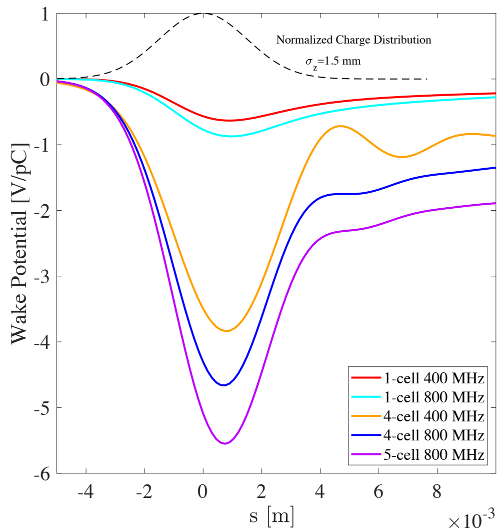
Need to study impact on beam operation, e.g. dispersion control, and components

Selected Recent Progress

Ramping **magnet challenge**
At 14 TeV, energy in field is O(200 MJ)
Need to recover it pulse to pulse
Started to develop **powering scheme** with energy recovery

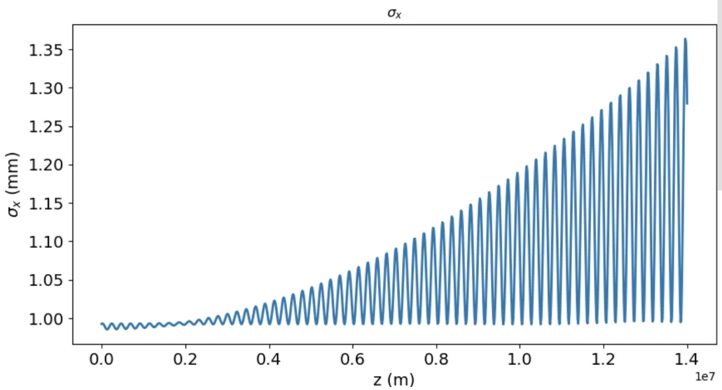


D. Aguglia
F. Boattini
G. Brauchli



S. Zadeh
U. van Rienen

RF challenge (also for FFA):
High efficiency for power consumption
High-charge (10 x HL-LHC), short, single-bunch beam
Maintain small longitudinal emittance
Studies on cavity wakefields and longitudinal dynamics started

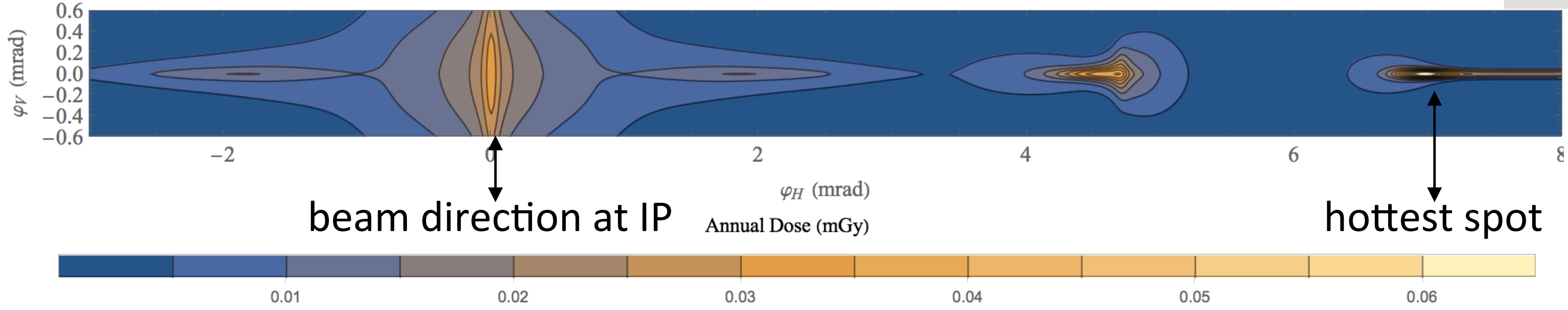


M. Magliorati
E. Metral,
T. Raubenheimer
D.S.

Collective effects might be a bottleneck
Revisiting for higher energies
Need to develop tools for collective effects in matter

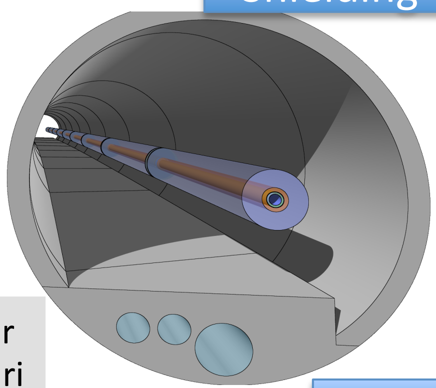
Selected Recent Progress, cont.

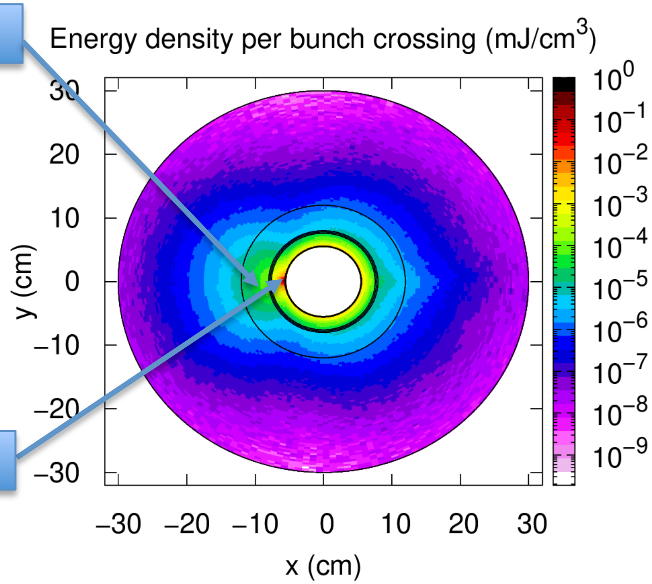
C. Carli



Collider Ring Lattice Design:
Based on MAP design, lattice design for high energy is starting
Started production of **radiation maps** and identified hot spots around IP and in arcs
Need to include radiation considerations in lattice design

Loss challenge in collider ring:
Loss per unit length is constant
fewer, but higher energy particles
Simulations of shielding started



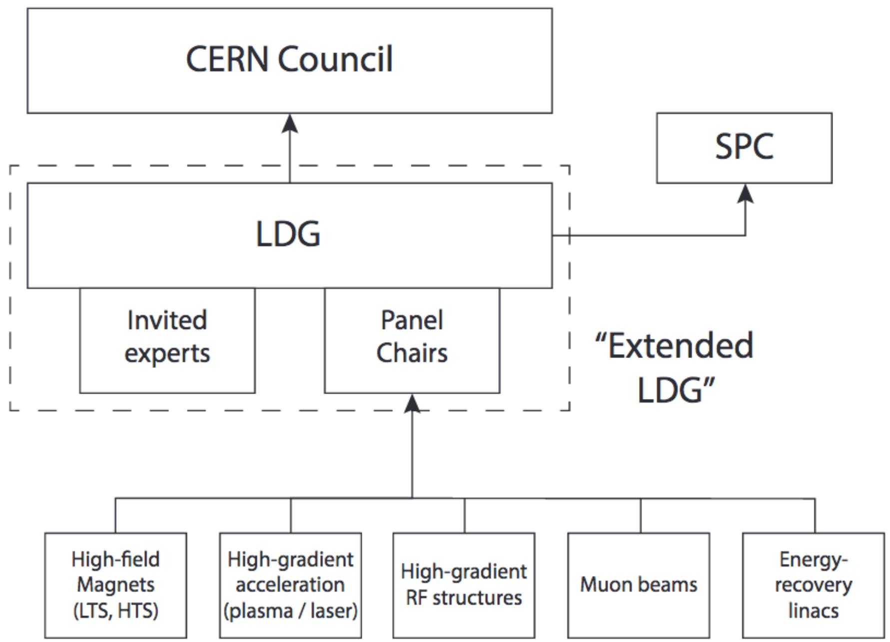


A. Lechner
D. Calzolari

European Accelerator R&D Roadmap

Council charged Laboratory Directors Group (LDG) to deliver European **Accelerator R&D Roadmap**

Panels
- Magnets: P. Vedrine
- Plasma: R. Assmann
- RF: S. Bousson
- Muons: D. Schulte
- ERL: M. Klein



Muon Beam members: Daniel Schulte (CERN, chair), Mark Palmer (BNL, co-chair), Tabea Arndt (KIT), Antoine Chance (CEA/IRFU) Jean-Pierre Delahaye (retired), Angeles Faus-Golfe (IN2P3/IJClab), Simone Gilardoni (CERN), Philippe Lebrun (European Scientific Institute), Ken Long (Imperial College London), Elias Metral (CERN), Nadia Pastrone (INFN-Torino), Lionel Quettier (CEA/IRFU), Tor Raubenheimer (SLAC), Chris Rogers (STFC-RAL), Mike Seidel (EPFL and PSI), Diktys Stratakis (FNAL), Akira Yamamoto (KEK and CERN)

Roles of panel members and European (other regions to be added) contact persons at https://muoncollider.web.cern.ch/organisation

Roadmap Milestones

Foresee three community meetings

- First meeting **May 20+21**
  - **identify R&D issues**
  - **first ranking, if possible**
- Then end of June/beginning of July
  - **Identify scope of R&D for next ESSU**
  - **Priorities, resource estimates, scenarios**
- End August/September
  - **final R&D list, internal priorities, resources estimates, scenarios**

LDG schedule

- **June Council**: present background to process
- **First R&D list**
- **July EPS-HEP**: public presentation of progress for feedback
- **Complete R&D list, first internal priorities, resource estimates**
- **Support of physics case**
- **September SPC / Council**: present of interim findings
- **Complete R&D list, internal priorities, resource estimates**
- **December Council**: gain approval of the final report

Global Collaboration

We do see this as a global effort

- profit from US expertise
- and new enthusiasm in Europe and revived enthusiasm in the US
- prepare to include the US in the collaboration after P5
  - and before, where possible
- include Asia

Submitted a number of proposals for white papers to Snowmass

- physics potential
- detector
- accelerator

Ideally, we will form a common collaboration with different proposed sites

Conclusion

The muon is a unique promising option at highest lepton energies

We need to fully explore the physics case, which goes well beyond 3 TeV (studied for CLIC)

Have to address the feasibility

A great challenge but also a great opportunity

Many thanks to all that contributed
MAP collaboration
MICE collaboration
LEMMA team
Muon collider working group
European Strategy Update
LDG
Muon collider collaboration
…

Web page: http://muoncollider.web.cern.ch

Mailing lists:
MUONCOLLIDER_DETECTOR_PHYSICS@cern.ch,
MUONCOLLIDER_FACILITY@cern.ch
go to https://e-groups.cern.ch and search for groups with "muoncollider" to subscribe

Reserve

Memorandum of Cooperation

Basically ready, waiting for final polishing

CERN is initially hosting the study

- International collaboration board (ICB) representing all partners
  - elect chair and study leader
  - can invite other partners to discuss but not vote (to include institutes that cannot sign yet)
- Study leader
- Advisory committee reporting to ICB

Addenda to describe actual contribution of partners

Goals of First Community Meeting

Meeting of working groups and plenary session

- but working groups should prepare beforehand and only finalise at the workshop

The goal is to identify the R&D that has to be carried out before the next ESSU-PP to scientifically justify the investment into a full CDR and a demonstration programme. This includes R&D to develop a baseline collider concept, well-supported performance expectations and to assess the associated key risks, cost and power drivers. Further, the main components of the demonstration programme should be identified together with the corresponding preparatory work.

The working groups should propose realistic but ambitious targets for the performance goals of the different collider systems. In particular they should consider what could be demonstrated in a test facility starting in 2026, as well what one can anticipate to be available in 2035-2040 for a first collider stage and in 2050 for an energy upgrade.